

Measuring Soil Wetness with TDR

Use of TDR (time-domain reflectometry) to measure soil wetness is based upon the fact that water has a much higher dielectric than other materials:

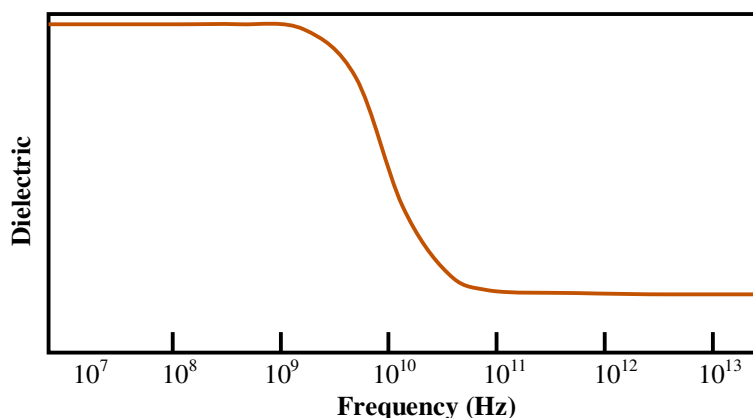
Material	Dielectric
Water	80
Ice	3
Air	1
Soil minerals	3-7
Soil organic matter	2-5
Vacuum	0
Ethanol	24

which means that the composite dielectric of a soil is largely determined by the wetness. In practice, use of the dielectric to estimate soil wetness depends on two steps:

- 1) How do we measure the dielectric of a soil?
- 2) What is the relationship between the dielectric and the soil wetness?

Measuring the dielectric:

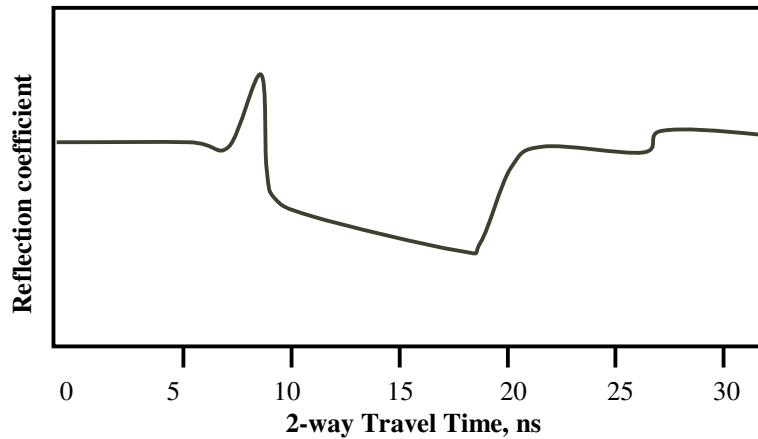
The dielectric (also called relative dielectric, dielectric constant, relative dielectric permittivity, and a few others) is a (dimensionless) measure of the ability of a material to oppose charges, to compensate internally for charges. In water, this compensation is accomplished by the polar water molecules rotating to align themselves with the gradient. If we used direct current (DC), the molecules would stay aligned, but if we use alternating current (AC), the molecules will keep changing orientation as the direction changes. Notice that if the current alternated too fast, the molecules would not be able to reorient themselves quickly enough, and the dielectric would go to zero: it is therefore not a constant, but a function of frequency:



Bottom line: as long as the frequency isn't too high, we can get a good measure of the dielectric of the composite (solids, air, water).

The dielectric is measured using a TDR probe (a waveguide with 2 prongs) and a "cable tester", a sort of wave-generator plus oscilloscope. We send a voltage step pulse down a wire into the TDR probe. The signal travels down the waveguide, bounces off the end,

and returns to the wave generator/oscilloscope. The information that comes with the bounced pulse is in the form of a reflection versus time plot:



The pulse time between the start of the valley after the peak around 8 ns, and the bottom corner of the valley (around 18 ns), is the travel time we're interested in. This section corresponds to the time spent in the waveguides (i.e., affected by the soil), and the dielectric ϵ is related to the travel time of this section of the plot by $\epsilon = (ct / 2L)^2$ (c = speed of light, and L = length of the waveguide).

Obtaining wetness from the dielectric:

The volume wetness can be related to the dielectric by the original “Topp’s equation,”

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon - 5.5 \times 10^{-4} \epsilon^2 + 4.3 \times 10^{-6} \epsilon^3,$$

an example of how NOT to analyze data (and don't even bother to write down this equation, or to memorize it!). I say this because the above equation has no theoretical basis: the researchers just used a general polynomial to fit to the data. After some further investigation into the physics, other researchers eventually realized that the volume wetness should be related to the square root of the dielectric. So now we just say

$$\theta = 0.115\sqrt{\epsilon} - 0.176,$$

which is much easier to remember and to write. More to the point, it has some physical meaning, and there is some reason to believe that it will work outside the range within which it was originally fitted. (Note for those remaining fans of polynomials: outside the original data range, polynomials are notoriously bad for prediction. If you go far enough outside the original data range, every polynomial will eventually go to positive or negative infinity. Unless you have a good reason to follow the function to positive or negative infinity, don't use it. You should know enough about the physics of what you're doing that you have a reason for the equation you fit to your data. That way, the equation will mean something, and your research won't be laughed out next year in favor of the short article by the young whiz who explains what all your hard work actually means.)

Where does the “-0.176” in the equation come from? If water content is linear with the dielectric, there should be a zero intercept. But other things in the soil also have a non-zero dielectric. The big one is clay. The actual clay content will change the intercept (-0.176 in the equation above). In theory, you should be able to calibrate your TDR to a

specific soil by taking a single measurement (1 equation, 1 unknown), mainly to account for clay content. Note that it probably isn't the clay itself that affects the dielectric directly; rather, it's the effect that clay has on water. The first few molecular layers near the clay surface are somewhat constrained in their movement, and because the dielectric is measured by causing the molecules to move in response to an electrical field, constraining their movement will affect the measured dielectric.

The TDR-based calculation of water content is also affected by temperature and by salinity. So we have 4 variables – frequency, clay, temperature, and salt – that you need to be aware of.

The TDR probe is a handy device for combining with other sensors and/or measurements. For example, because the probe has 2 parallel metal prongs, it can be used to measure electrical conductivity (which generally isn't interesting in its own right, but it can be used to infer other things, such as salt concentration). Some researchers have put thermocouples inside a probe, allowing them to measure temperature; others have put in a small heater wire as well as a thermocouple, enabling measurement of some thermal properties. Our group here at ISU has actually gone one step beyond that: using one heater prong and two thermocouple prongs (say, one above and one below the heater), we can also calculate the soil water flux density.

Finally, an important point to keep in mind. All the methods we have discussed are indirect, except for the “definition” method: taking a soil sample, weighing it, drying it, and weighing it again. This method is labor-intensive (especially for deep samples) and destructive; however, it is the only direct method. It is, therefore, the reference against which all other methods are tested.